Optimization of a Turbine Blade Performance Due to Active Control of the Vortex Dynamics

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Abstract

Geometry and thermal stratification of the flow around a turbine blade specify this flow as one affected by buoyancy and centrifugal forces. An approach is proposed and tested of a boundary-layer control under body forces using generation of counter-rotating streamwise vortices that are an inherent vortical structure of such flows. The active mode of vortex generation is realized due to an imposed surface temperature gradient periodic in the spanwise direction, which must be correlated with basic flow parameters. Values of two independent variables, temperature gradient and spanwise scale of induced vortices, can be adjusted to current flow conditions thus changing the vortex dynamics in a favorable way.
Velocity fields and spectrum redistribution in boundary layers with embedded streamwise vortices show efficiency and prospects of the proposed method to control flow characteristics.

1. Introduction

Flows of practical interest for engineering applications are the flows under body forces which can account for a complex geometry of a body, flow-body temperature difference, gravitational or electromagnetic fields for some types of fluids. It means that to be efficient, the boundary-layer control techniques must be

- correlated with specific features of the vortex dynamics of such flows;
- flexible or active i.e. allowing to adjust control parameters to changing flow conditions or to any other requirements of a unit operation;
- simple and reliable in design, operation and long-term exploitation;
- based on the advanced fundamental science involved to solve formulated problems and to use practical experience including successful results obtained due to numerous trial-and-error methods.

Recognized common features of vortex dynamics distinguish a group of flows, which can be studied under rigorous formulation of the problem [1, 2, 3]. These are flows of viscous fluid affected by body forces (e.g. centrifugal forces or buoyancy). Balanced interaction between body forces (because of the surface curvature or its temperature different from one of the fluid) and viscous forces (because of the wall presence) gives rise to the development of streamwise vortices in boundary layers. Being an essential item for fundamental analysis of boundary-layer problems related to the laminar-turbulent transition and turbulence production, this flow structure is of interest for applied studies related to the fluid transport control.
One of such typical and important applications deals with the improvement of low-pressure turbine blade performance, which is strongly influenced by unsteady flow separation and transition. It is connected with the specific conditions of a gas turbine engine operation from take-off to high altitude cruise causing significant variations of Reynolds number. Since the flow around a turbine blade is a turbulent flow affected by centrifugal forces and buoyancy, it can be investigated and controlled in the frame of known general formulations.

In this connection, extensive studies of a boundary-layer flow over a concave surface were carried out on a basis of the classical Goertler stability theory [4, 5] and receptivity approach [6, 7]. They provided an insight into

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mechanisms of the vortical structure evolution and behavior on condition of natural (unforced) emergence and development of streamwise vortices as well as of their generation with a given scale. Matched experimental and numerical investigations [8, 9] showed vortex scale transformation occurring downstream and across boundary layer that should be taken into account in applications of the obtained fundamental results.

The objective of the present work is to show that regular streamwise vortices are an effective control structure to maintain preferable scales and amplitudes of fluid motion in a boundary layer under body forces what can be applied for optimization of turbine blade performance.

From a viewpoint of basic studies, it means special organization of the surface-flow interaction aimed, e.g. to delay early flow separation. From a viewpoint of technological applicability, it means the development of a reliable, convenient and flexible way of flow management with minimum energy outlay. Practically, the work consists of the following interconnected parts,
(1) analysis of a flow around a turbine blade;
(2) establishment of typical features and scales of vortical motion for a set of basic flow parameters of interest;
(3) controllable stimulation of the vortical motion of a similar type but of different scale and intensity depending on parameters and objectives of a formulated task.

2. Analysis of a flow around a low-pressure turbine blade

A key point of the present investigations is generation of streamwise vortices with given parameters in a flow where this type of motion is inherent, i.e. in boundary layers affected by body forces. The present formulation of the problem originated from a practical need to improve flow conditions around a low-pressure turbine blade. First of all, it deals with the development of a simple and reliable method to control flow separation on a suction side of the blade. Figure 1 illustrates the configuration of the flow field around a low-pressure turbine blade showing a position of a separation bubble on its surface [10].

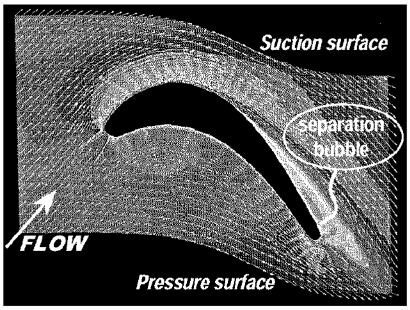

Figure 1. Velocity field pattern around a low-pressure turbine blade; 1/2 cascade passage

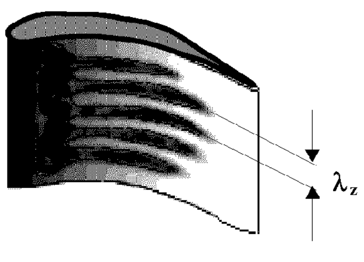

Figure 2. Visualized streamwise vortical structure on a pressure side of a low-pressure turbine blade

To estimate space-scales of a vortical motion in a boundary layer over the turbine blade that can be taken as a reference value for the flow control purposes, one can assume it to be of the order of regular vortices found due to liquid crystal visualization on its pressure side. Figure 2 gives an idea about this naturally self-organized streamwise vortical structure arising at Re_C =67,500 with a scale λ_z=8 mm (Re_C is a cord-based Reynolds number). Analysis of the boundary-layer vortex dynamics in the frame of Goertler stability theory explained physical mechanisms of the vortical structure formation [7] and enabled the formulation of present studies.

In particular, non-dimensional wavelengths of the experimentally observed 8-mm scale vortices were estimated according to the well-known centrifugal stability diagram. They were found to be $\Lambda=\lambda_z^{3/2}Re_C/cR^{1/2}$=24-36, for typical values of Re_C=67,500 and 100,000. The Λ values appeared to be close to "neutral", $\Lambda\approx39$, scales, i.e. those having zero amplification rates for a wide range of Goertler numbers, $G=U_0\delta_2^{3/2}\nu^{-1}R^{-1/2}$. It means that the streamwise vortical structure naturally arising in the boundary layer of a low-pressure turbine blade trends neither to grow, nor to decay in a downstream direction. However turbulent environment (or in general, not ideal flow conditions like considered in the stability theory) does not help to maintain this structure far downstream and thus to provide a necessary thermodynamic balance in a boundary layer preventing its separation.

Therefore efficient flow control techniques in such situations are those bringing minimal amount of energy to save the natural deterministic flow structure as long as possible. This mechanism of the flow control can be understood and applied in the frame of the receptivity problem. In the case under consideration, it means the investigation of a boundary layer response to generated streamwise vortices, which are an inherent element of the flow affected by centrifugal forces. In general case, vortex dynamics of the flow around a turbine blade can be considered as a prototype problem to study the vortical structure evolution in boundary layers under centrifugal forces and possibilities to effectively manipulate this structure.

3. Investigation approach and methods

To reveal physical mechanisms of the studied phenomena, the Goertler stability theory [4, 9] was assumed as a basis. The stability diagram was used as a reference for the scale choice of induced vortices, which covered a range from neutral ones to those most amplified according to the theory.

Experiments were carried out over a bottom of a water channel (10 x 25 x 300 cm test section) containing a changeable concave part with a curvature radius, R = 1.0, 4.0 or 12 m [6]. Values of a length-based Reynolds number and of a Goertler number based on a momentum thickness were maintained correspondingly in a range of Re_x=(0.6-1.0)x10^5 and G_θ≈0.3-10.0.
A flow field was visualized using electro-chemical Tellurium method similar to the well-known smoke-wire visualization technique in air. It gave very informative for these studies wavy $U(z)$ velocity distributions [9] similar to those shown in Figure 3. In addition, hot-wire measurements were carried out (using one-component probes of a DISA system) at U_0=0.1, 0.2 and 0.6 m/s that enabled to get spectral characteristics of the boundary layer. These flow conditions corresponded to subsequent stages of the natural laminar-turbulent transition manifested in a form of propagating Tollmien-Schlichting waves, formation of streamwise vortices and their breakdown to turbulence. Hot-wire probes were placed at y=4mm from a test surface and at Δx=5 cm downstream of the vortex-generator array, i.e. in a region of the most intense interaction of natural and generated disturbances. Both normal velocity profiles and spectral characteristics were measured at three spanwise positions along λ_g (as shown in Figure 3) corresponding to downwash (z= 0) and upwash (z=λ_g/2) interfaces between neighboring vortices and between these two positions (z=λ_g/4).

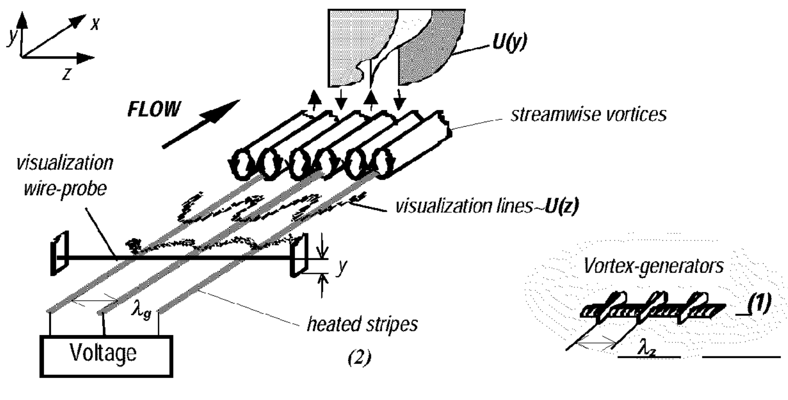

Figure 3. Sketch of the experiment

Streamwise vortices were induced using mechanical vortex-generators (1) having been mounted on the surface regularly in z-direction at a λ_g distance from each other. Besides, electrically heated flush-mounted stripes oriented downstream and separated from each other by thermally insulated stripes were proposed as an engineering solution to initiate and maintain necessary flow structure. It meant a boundary condition given in a form of a changeable z-periodic temperature gradient, ΔT (z). Compared to known techniques to influence the near-wall region (e.g. like riblets), such a solution enables to keep the surface smooth that is undoubtedly beneficial from operational and technological viewpoints. In addition, an active regime of the vortex dynamics control can be realized imposing different configurations of surface temperature fields strictly correlated with the basic flow parameters. Primarily, it relates to the spanwise scale of induced vortices, λ_z, (temperature pattern over the surface) and to control ΔT values (local T temperature of the heated stripes), both characteristics depending on operation requirements.

4. Spectral response of boundary layers to generated vortical structures

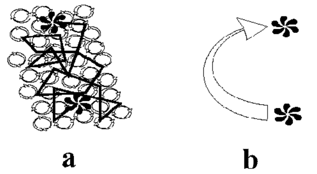

Figure 4. Patterns of fluid transport in (a) homogeneous vortical fields and (b) those containing large-scale vortices

Specific features of flow fields with available large-scale vortices are caused by their longer lifetimes compared to the smaller scale motion as illustrated in Figure 4 [11]. It shows that once trapped by a large-scale vortex, a fluid particle is transported to significant distances without a noticeable change of direction. Such prevailing mode of motion defines specific mechanisms of momentum, heat and mass transfer as well as specific ways of their description.

In spectral terms, a role of large-scale vortices in fluid transport near a wall is recognized due to their basic contribution to the long-wave "energy-carrying" part of the turbulent kinetic energy spectrum. Deterministic investigations of a streamwise vortical system supplemented with the general studies of energy redistribution between a long-wave and inertial intervals of turbulent fluctuations can bring deeper insight into the phenomena mechanisms and formulation of basic principles of flow control.

Figure 5 shows a typical spectrum of turbulent fluctuations.
Short-wave part of the spectrum corresponds to dissipation scales of fluid motion characterized by comparatively low kinetic energy, which transforms into heat due to available viscosity. The long-wave part of the spectrum contains a main part of turbulent energy and dominates in the course and type of transport processes. Therefore large and medium-scale vortices contributing to the energetic and inertial intervals of the spectrum are most important for fundamental studies dealt with practical applications.

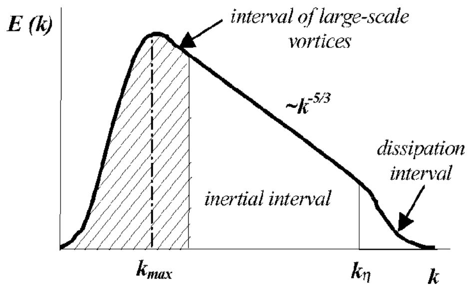

Figure 5. Spectrum of turbulent fluctuations (*η - Kolmogoroff's lengthscale)*

Thus, the analysis of spectral properties of a near-wall flow with embedded large-scale vortices both in laminar and turbulent environment can show important aspects of the vortical structure evolution under natural and controlled conditions. In its turn, better understanding of the vortex dynamics must bring to optimal ways/techniques to interfere the process so that to sustain a favorable structure for a formulated flow control problem.

Large-scale streamwise vortices were generated in transitional and turbulent boundary layer using a vortex-generator array mounted on a surface normally to the free-stream velocity vector (see Figure 3).

First, fluctuating streamwise velocities were measured in naturally developing transitional and turbulent boundary layers, i.e. without vortex generation. Standard procedure using fast Fourier transform was applied to recorded hot-wire signals to get the results depicted in Figure 6. Reference spectral curves are shown here both for transitional and turbulent boundary layers. The turbulent reference curve 4 obtained closer to the wall displays more uniform, smoothed spectral pattern than the curve 3 due to statistically dominating smaller scale vortices. Analysis of the transitional case (curve 2) brings to a conclusion that streamwise vortices naturally developing during laminar-turbulent transition result in a specific energy distribution along the spectrum characterized by a strongly pronounced long-wave interval with an amplitude peak around $k \approx 0.5$.

Table 1: Vortex-generation and flow parameters (curve 1)

λ_g, cm	U_0, m/s	y_{vg}/δ_l	y/δ_l	y/δ
1.2	56.0	1.22	0.615	0.091

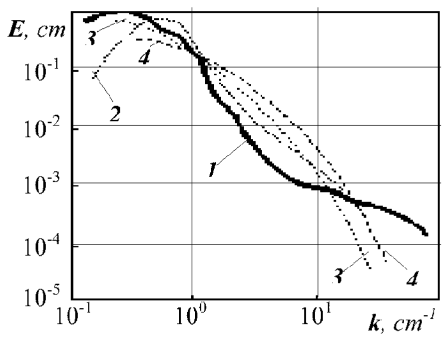

Figure 6. Power density spectra of u'-velocity fluctuations in boundary layers:
1 – in case of generated streamwise vortices;
2 – reference curve for natural laminar-turbulent transition, Re~10^5, y/δ_l=1.08;
3-4 – reference curves for turbulent boundary layers, Re~10^6, y/δ=0.21 (3), y/δ=0.063 (4)

At the same time, the large-scale motion significantly suppresses intensity of fluctuations in the inertial interval ($0.5<k<20$) but increases dissipation (spectral components of $k>10$).

A legend for experimental conditions of vortex generation is given in Table 1. Here y is a distance of a hot-wire probe over a surface, y_{vg} is a normal size of vortex-generators, δ_1 is a boundary-layer displacement thickness, δ is a boundary-layer thickness.
The obtained results (curve 1) explicitly show that even in case of fully developed turbulent flow, generated streamwise vortices change the boundary-layer characteristics redistributing spectrum in favor of its long-wave part, i.e. approaching the transitional spectral pattern. To some extent, it can be considered as flow relaminarization with appeared deterministic vortical elements. Practically, it shows a way to change transport properties near a wall both in transitional, and in turbulent boundary layers.

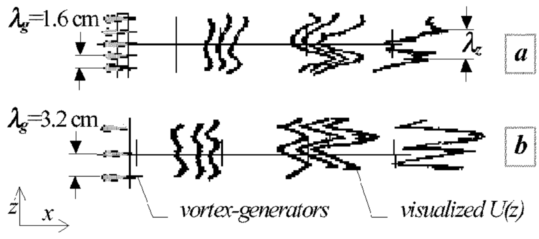

Figure 7. Boundary-layer flow response to twice differing scales of generated streamwise vortices

Spanwise velocity profiles (as a sensitive indicator of embedded streamwise vortices [3, 9]) were registered for the same flow and control (vortex-generation) conditions. They clearly demonstrated different receptivity of boundary layers to the scale of generated vortices. For instance, if a process of natural transition to turbulence was at the stage of self-formation of streamwise vortices, controlled excitation of smaller scale vortices could be seen as superposition of two *U(z)* waves (Figure 7,a): generated small-scale λ_g and naturally developing large-scale λ_z vortices. In spectral terms, it meant energy redistribution into a more uniform spectrum (without a sag in the inertial interval). It can be interpreted as an effect of turbulization since the spectrum shows a good agreement with the turbulent reference curve 4 obtained in the vicinity of the wall. The lower pattern of Figure 7 demonstrates adequate reaction of the boundary layer to introduced vortices. It corresponded to a spectrum similar to one shown in Figure 6, case 1, i.e. it evidenced available streamwise vortices.

Thus, depending on a match of generated vortex scale and basic flow parameters, one can expect to obtain either large-scale deterministic vortical structure typical for laminar-turbulent transition (here, flow "relaminarization") or dissipative small-scale vortices (flow "turbulization").

5. Thermal excitation of streamwise vortices

Flow fields taking place in practice around operating units like turbine blades are far from the idealized numerical or laboratory conditions where types and values of disturbances introduced in a boundary layer are strictly defined and dozed. To approach the applicability of the analyzed flow control method based on excitation of the organized vortical structure, it was tested using another way of vortex-generation (Figure 3 (2). Besides, to model effects of random uncontrolled factors, heated longitudinal stripes were flush-mounted in a thermally insulated plate that provided, on the one hand, necessary temperature gradient $\Delta T(z)$, and on the other hand, influenced the boundary layer through the surface compliance.
Such surface properties are known to damp any near-wall disturbances. Therefore it must be very demonstrative to see a combined effect of a generally mild $\Delta T(z)$ influence and that of the compliant surface. Three values of temperature T were used in the experiments corresponding to electric power applied, P_1=0 (no influence), P_2 =7.8 W and P_3=12.2 W. The $\Delta T(z)$ control effect was registered at two distances from the wall, y=2 and 3 mm. shown accordingly in left and right pattern sets of Figure 8. As it was mentioned above, flow-field visualization in xz-plane yielded sensitive and convenient $U(z)$ characteristics to estimate a boundary layer response to certain excitation and, subsequently, to choose the control parameters.
(a) The first $U(z)$ patterns of both sets, reference velocity profiles, show varying in time $U(z)$ shape that is an evidence of a started meandering motion of a streamwise vortex system or their strongly unsteady behavior.
(b) The available z-periodic mechanical properties of the surface (due to rigid longitudinal stripes implanted in the compliant basement) stabilize $U(z)$ velocity distributions at different distances from the surface hampering the naturally developing meandering motion in the boundary layer; however the $U(z)$ amplitude stays large enough characterizing a significant rate of transition to turbulence. Besides, the spanwise periodicity of visco-elastic properties of the wall appears to be not a strong boundary condition to introduce a given smaller-scale, λ_g=1.2 cm, vortical structure in a boundary layer.

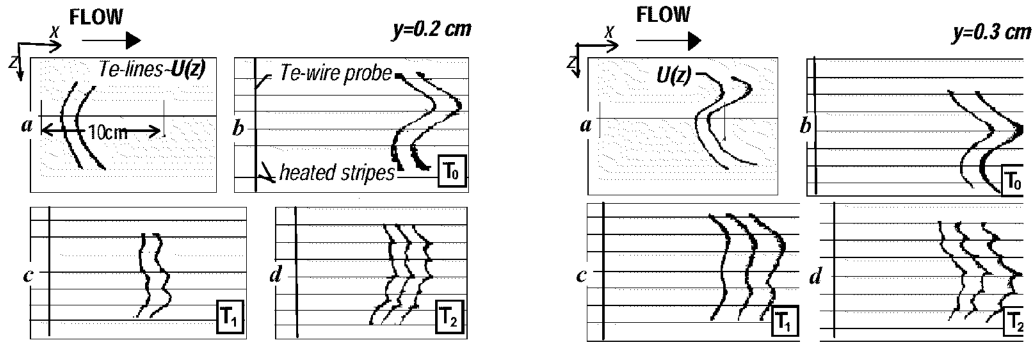

Figure 8. Visualization of a boundary layer over a concave surface controlled by the heated stripes, $Re{\sim}10^5$, G_ϑ=2 (U_0 =5 cm/s, x=2.18 m; R=12 m); y=2 mm (left set); y=3 mm (right set);
a: natural development of transition; **b-d**: excitation of longitudinal vortices, λ_g=1.2cm:
b – unheated stripes, $T=T_0$ =20°C; ***c, d*** - heated stripes: $T_2 > T_1 > T_0$

(**c**) Moderate heating (corresponding to the value of electric power P_1~7.8 W) straightens $U(z)$ velocity profiles; it can be interpreted so that the transition rate decreases here compared to the undisturbed case. However visualized flow patterns show yet almost twice larger spanwise scale of the developing vortical structure than one induced by the heated stripes, i.e. λ_z=2.4 cm=2λ_g.

(**d**) A higher ΔT value (P_2=12.2 W) keeps the averaged $U(z)$ profile straightened along a whole length of the control section and downstream; in addition, it induces the smaller-scale vortical structure corresponding to the scale given by the stripe disposition. It should be noted, that while being noticeable in the vicinity of the wall (y=2 mm), it transforms into a larger scale structure in the outer part of the boundary layer (for comparison, see patterns of Figure 8, **c**, left and right sets).

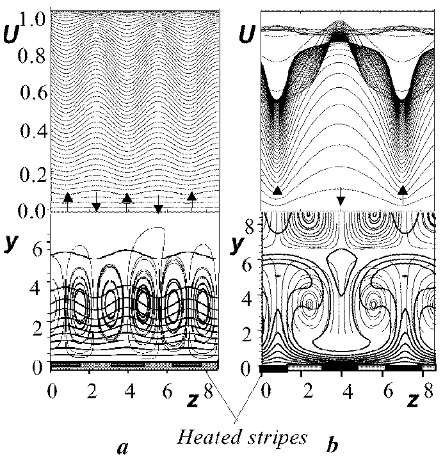

Figure 9. Calculated consecutive stages of the velocity field and flow topology (iso- velocity contour lines) development over a surface generating streamwise vortices

A tendency of the forced small-scale structure to grow was observed both experimentally and numerically for all considered modes generated in a boundary layer, i.e. for nondimensional vortex scales Λ<240 according to the Goertler stability diagram. However the life-time of incoming (or generated by any means) small-scale vortices, or their self-sustaining ability, depends very much on the spanwise scale of the forcing factor correlated with the basic flow parameters. It is well seen from comparison of the two numerically considered cases [9]:

(*1*) excitation of the pure second mode, Λ_2=84, and

(*2*) slightly "incorrect" excitation of Λ_2 that assumed a spectrum, rather than a single mode induced, including the most amplified first mode. It means a little irregularity in the arrangement of the heated stripes what is very probable in practice; numerically, it was introduced through a shifted first stripe as well.

In both cases, the constant boundary condition imposing the permanent preference to a given vortex scale could not prevent from developing and final dominance of a larger scale vortical structure. However in case (*1*) shown in Figure 9, the flow structure transformation took a longer time, while in case (*2*), the initially strongly prevailing second mode gave up almost immediately to the first one. Experiments showed even more slow vortical structure evolution to its breakdown if vortices were generated with a scale close to the neutral one. It proved a possibility to control the vortex dynamics and, through chosen dominating scales of motion, to influence momentum transfer in a boundary layer.

Practical benefit of embedded streamwise vortices is demonstrated in Figure 11 in a form of the boundary layer separation control over a surface of complex configuration. The top view of a visualized flow field shows

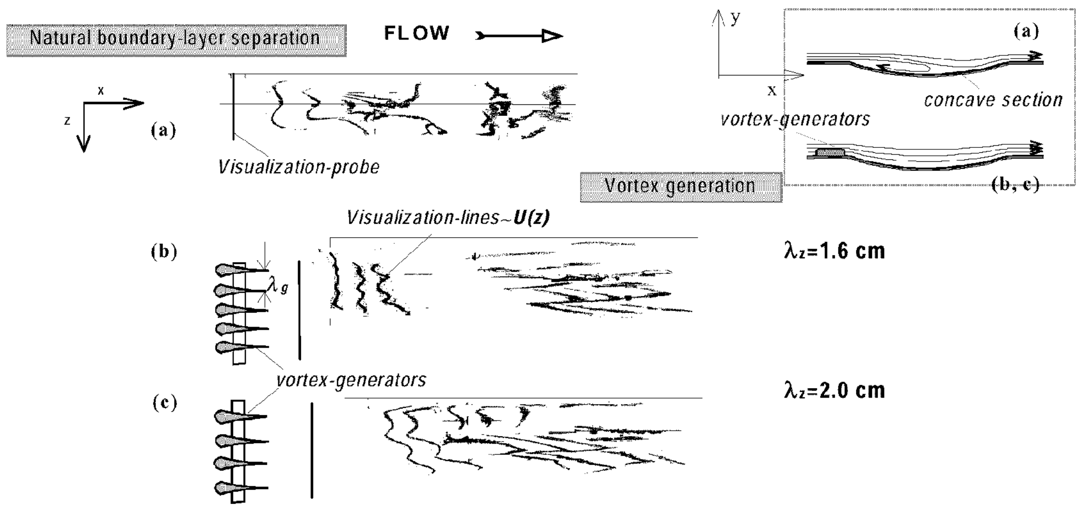

Figure 10. Boundary-layer separation control using generated streamwise vortices, U_0=7 cm/s, R=4 m

immediate flow separation (a) downstream of the rounded backward surface step, while vortices generated upstream of the critical point make the flow pattern orderly with the space-scale of the vortical structure corresponding to the one induced. Preliminary tests (using liquid-crystal visualization) of a turbine blade with flush-mounted electrically heated stripes showed similar encouraging results, i.e. a separation line shifted downstream under voltage applied to the stripes.

Conclusions

An approach to performance optimization of a turbine blade was formulated and realized with a primary assumption about a boundary layer as a viscous flow affected by centrifugal forces. In this connection, Goertler stability theory and receptivity methods were attracted to get an insight into the vortex dynamics and possibilities of its control in a required way. The basic idea was the utilization of the inherent structure (streamwise vortices) of the flow under body forces.

A method was proposed and developed of non-intrusive generation of streamwise vortices with a given scale. It is based on heating of a flush-mounted array of longitudinal elements (stripes) regularly spaced in the spanwise direction. Depending on boundary conditions given by a distance between the adjacent heated stripes λ_g, and their temperature gradient with an ambient flow ΔT, properties of the induced vortex system (space scale, intensity and growth rate) could work in a desirable way. Choosing the values of the control parameters, one can get either prolonged, low-rate vortex field development with stabilized smoothed velocity profiles or direct generation of streamwise vortices with a given scale, moderate long-term or well-pronounced short-term effects.

Obtained experimental and numerical results are in a good agreement having revealed typical characteristics and response of a boundary layer to generated streamwise vortices:

- growing scales of the dominating vortical motion both downstream and normally to the surface;
- mode competition in favor of definitive prevalence of a large-scale fundamental even under condition of a constant different-scale forcing from the wall;
- non-zero receptivity of both transitional and turbulent boundary layers under centrifugal forces to induced streamwise vortices;
- power spectra redistribution in favor of a long-wave interval in transitional and turbulent boundary layers with embedded streamwise vortices that directly influenced transport properties of a near-wall flow.

The latter was shown can be manipulated as required and be applied, e.g. for the flow separation delay.

Governing ideas and methods of the flow control tested for laminar/transitional boundary layers proved to be efficient in case of a developed turbulent boundary layer that is more congruous to practical applications, in particular, related to the improvement of the turbine blade operation.

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